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Material properties extraction of the stator core of a 50 kW permanent magnet synchronous motor (PMSM) by means of nondestructive testing method

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Abstract

In this research physical (e.g., density) and mechanical (e.g., Young's modulus, etc.) properties are extracted via non-destructive testing (NDT) method for the stacked stator core of a 50 kW permanent magnet synchronous motor. Mechanical properties like Young's modulus, Poisson's ratio, etc. are essential parameters for the mechanical design of a component. As known, electric motors are comprised of two main parts, namely stator and rotor. In permanent magnet (PM) machines, the rotor of the electric motor includes some permanent magnets instead of windings; but the stator consists of windings to form the magnetic field. The stator core is made of a stack of coated electrical steel sheets or laminations, which are pressed together with tension bolts and tension bars or welded together in some cases. This matter causes different mechanical properties in axial and other directions. For electric machines such as induction and synchronous machines, the stacking pressure determination of the stator core is one of the major steps in machine design. The integrity of the stator core depends on the proper implementation of aforementioned step. The stacking process of the stator core of this type of electric (PM) machine comprises of three main stages including applying the stacking pressure, laminations welding under pressure, and releasing stacking pressure. These steps run as some static processes. In this study, the density and Young's modulus of the stator core of a certain 50 kW PM electric machine in various directions are extracted using a non-destructive testing method. The non-destructive testing method utilized in this work is experimental modal analysis. Using the natural frequency obtained from modal test as the objective function and implementing the FEM optimization, the material properties are presented.

Keywords: modal analysis; FEM optimization; PM electric machine; material properties.

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1. Introduction

Electric machines have a wide application spectrum in various industries such as transportation, petroleum, energy, marine, etc. For electric vehicles, the electric machine has an important role as the propulsion system that facilitates the motion of the automobile. Mechanical investigations of the stator core are stress analysis due to shrink-fit joint between the frame and the core, and the other investigation is stacking analysis. To reach a good and safe design for every component, it is necessary to use true values of material properties in analysis. The stator core axial properties are different from the laminations properties and essentially depends on the stacking pressure and coated laminations. These properties can not be extracted from the standard tension or compression testing methods. In this survey, we want to introduce Young's modulus of the stator core in axial direction via modal test and FEM optimization. To this end, an experimental modal test (bump test or hammer test) is executed (to discover the longitudinal natural frequency of the stator core), and then the stator core longitudinal frequencies are calculated by the FE method, while initial Young's modulus is assumed. The results of FE modal analysis (i.e., longitudinal natural frequency) in the first stage may not meet the results of the experimental method, so we should change the Young's modulus in the axial direction and run the simulation again. This operation repeats until the results of the simulation coincide with the true (yielded from the experiment) values. Thus, the final value is introduced as the Young's modulus of the stator core in the axial direction. There are common ways to determine the electrical properties of the stator core laminations such as Epstein or Single Sheet Tester (SST) measurement on an individual lamination of the stack, which includes standard testing methods [1]. One of the most popular approaches to determining the mechanical properties of materials is the tension or compression test. However, these methods are not applicable to the stator core of electric machines [2].

Zec et al. [3] have presented a finite element analysis for the calculation and evaluation of three-dimensional eddy current problems using the logical expressions (LE) approach, especially for the parts in motion. Yin et al. [4] have investigated modal analysis and material properties of the stator of a PM machine. In this survey, the initial value of equivalent material parameters is determined by analysing the equivalent models, and then the FE method is used to investigate the effects of equivalent material parameters on natural frequencies. Also, modal analysis of the stator core and the windings is done via FE and experimental methods. In another research [5] the effects of compressive stresses on the magnetic properties of a core stack are checked out. To this end, a prototype that dimensionally coincides with the main model has been fabricated, then the experimental tests are performed. Results of this work show that high compressive stresses in the stator core stacks result in a lack of magnetic properties of the system. In other references [6-8] modal analysis of the stator core stack of various types of electric motors is deliberated, in which mode shapes, and natural frequencies are obtained from analytical, FE, or experimental methods. The main components of the aforementioned electric machine are indicated in Figure 1.


(a) (b) (c)

Figure 1. (a) Stator set, (b) Wound stator without frame, (c) Rotor set

As mentioned, the mechanical properties of the stator core stack in the axial direction is different from laminations and there are no articles significantly focused on NDT methods for determining the mechanical properties of stacked cores. Thus the purpose of this paper is to figure out the material properties (individually Young’s modulus) of the stator core stack of a certain 50 kW PM machine, establishing a non-destructive testing method.

2. PM electric machine structure

The PM electric machine, like other machines, is made of two main stationary and rotary parts namely stator and rotor, respectively. The stator includes some main components, such as frame cover, core, windings, terminal box, and other secondary parts (e.g., cable glands, insulations, etc.). There is an essential difference between the frame cover of PM and induction or synchronous machines. Since the PM motors have very compact geometry, cooling requirements are fulfilled by designing a water jacket (several parallel conduits through the frame cover), while in others, cooling is facilitated via external or internal fan(s) and numerous fins on the outer surface of the frame cover. The core is formed of a stack of electrical coated laminations, which pressed together through the stacking process by special tools. The rotor in PM machines contains main parts including a shaft, stacked or casted core, and magnets. The number of magnets is determined according to the number of poles designed by electrical requirements.

3. Experimental modal analysis

After the disassembling process of the stator core (i.e. winding system detachment), the properties of the welded stator stack shall be determined by an experimental modal test. Experimental analysis consists of three main steps including preparation of appropriate boundary conditions, performing the test under laboratory status, and finally results analysis by the post-processing software. As known, there are three types of boundary conditions (BCs.), which apply certain constraints on a system and restrict the motion of the system. These BCs. contain clamped or fixed support, simply supported, and free boundary conditions. Free boundary condition is the most convenient and common condition utilized in experimental tests. The mentioned steps are described in the following sections.

3.1 Free boundary condition implementation

In this test free boundary condition is provided by a pile of sponges. The sponge is fabricated from foam materials, which are very soft and flexible in various directions. The described status is illustrated in figure 2.

3.2 Test execution

In this stage, system is ready to perform experimental tests. According to figure 2, the outer surface of the stacked core is divided into 8 regions; in fact, there are 8 sampling points in which every number is an excitation point. Sensor is installed in sampling point 1, and its ‘X’ axis coincides with axial direction, while ‘Y’ and ‘Z’ axes are in circumferential and radial directions, respectively. Mentioned descriptions are indicated in figure 3. The eZ-Analyst software is employed for post-processing purpose. We can use frequency Response function (FRF) obtained from sensor data. This process gives 755.6 Hz frequency shown in figure 4 for longitudinal mode shape.

Figure 2. Free boundary condition fulfilment

Figure 3. Sensor installation point and its axes directions

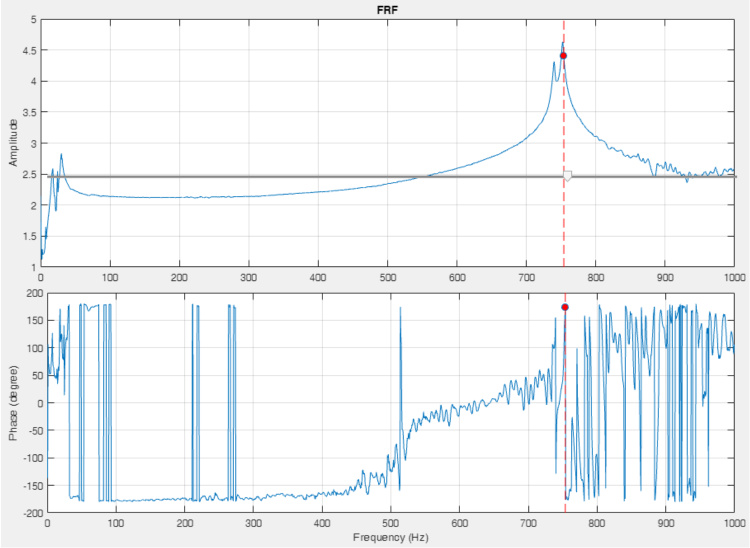


Figure 4. Frequency-amplitude response for experimental hammer test

4. Finite element analysis

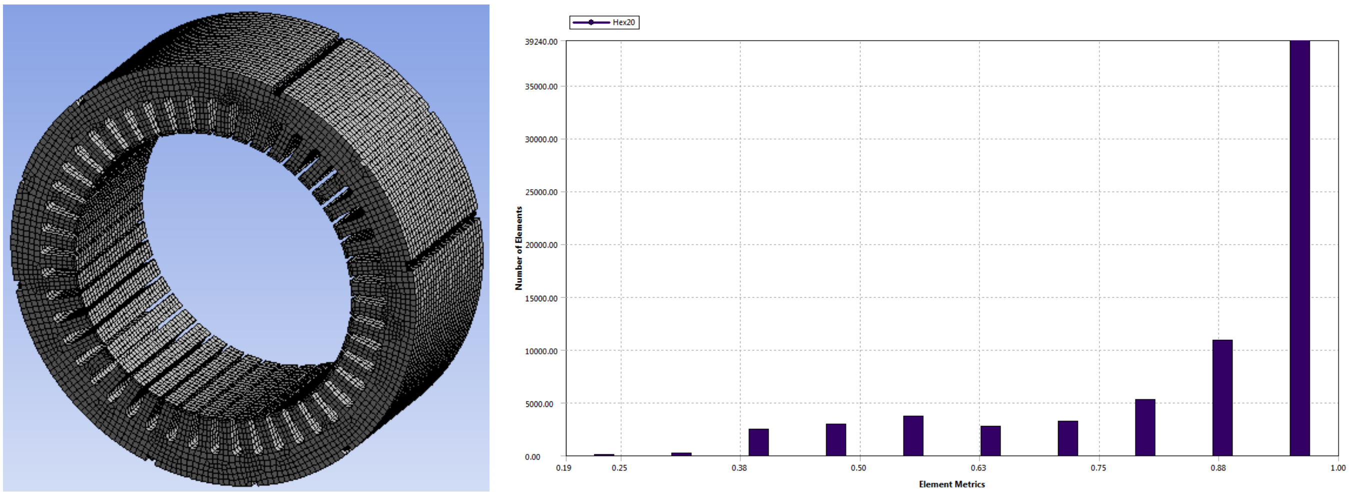
The solution method adopted for this case is Finite Element Method (FEM) implemented in Ansys workbench 2020 R2 software.

4.1 Simulation steps

FEM analysis includes four main steps as follows:

1. Material assignment
2. Connections and interactions
3. Mesh controls
4. Boundary conditions and external loads

After the body is simplified in the geometry module, the fourfold main steps are performed in the mechanical environment in FE software. In step 1, materials are assigned for every component. Here weld seams are made-up of isotropic materials which have 0.3 Poisson's ratio, 7800 kg/m^3 density, and 210 GPa Young's modulus. Also lamination base material is electrical sheet, which has 0.3 Poisson's ratio, 7650 kg/m3 density, and 210 GPa Young's modulus in its plane. In step 2, connections between weld seams and the stacked core are set as bonded and formulation is defined as MPC. In step 3, mesh settings such as element order, methods, and sizing are arranged to reach reliable model and results (figure 5). Very fine brick elements are defined in both weld seams and core. The quality of elements is mainly above 0.9, where the maximum quality can be reached is equal to 1. Since the experiment is conducted without any constraints, the FEM BCs. is considered as free ones. In other words, any constraints such as fixed support, frictionless support, etc. are not applied in any region of the geometry.



(a) (b)

Figure 5. (a) Meshed system with brick elements, (b) Elements quality

4.2 Solution

When all steps are completed and implemented correctly, the simulation is ready for running. Thus, preliminary results will be evaluated. It should be noted that the total mass and volume of the stacked core are measured as 15.35 kg and 2.0065e-3 m^3, respectively. Therefore the equivalent density is calculated as 7650 kg/m^3.

5. Results

In the processing stage, results of the primary simulation are available for investigation. These results are compared with the experimental outcomes. Since Young's modulus of the core is unknown, the primary value for this property is estimated as 450 MPa. The preliminary result shows that the axial fundamental frequency is obtained as 752.1 Hz with considering above properties. Also, the corresponding mode shape is exhibited in figure 6.

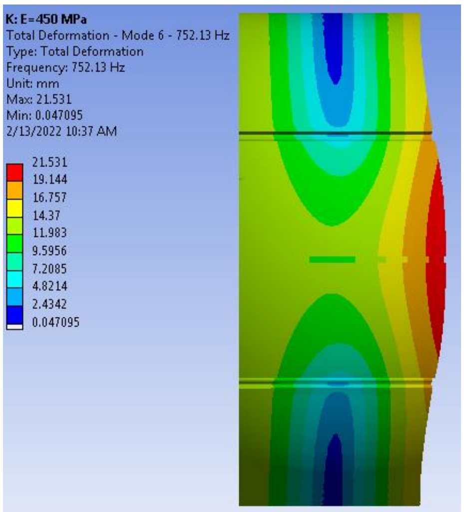


Figure 6. Corresponding mode shape for primary estimation

Since the evaluated frequency is less than its accurate value, the Young’s modulus is substituted as 500 MPa in the next estimation. After the solution is accomplished, longitudinal natural frequency is acquired 757.3 Hz, which its corresponding mode shape is indicated in figure 7.

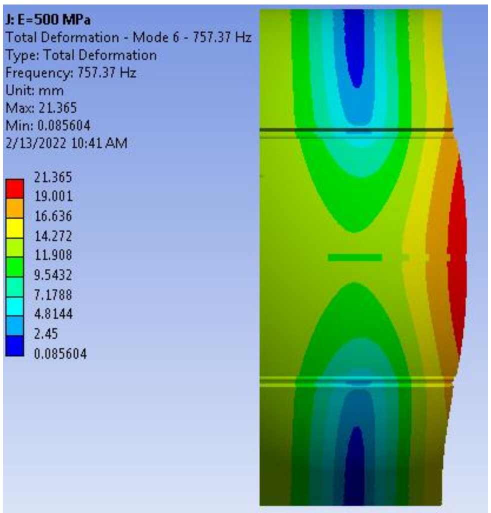


Figure 7. Corresponding mode shape for the second try

According to the past analysis achievements, it seems that the real value is between 450 to 500 MPa. Thus, it is a good approximation approach to use the interpolation method, as shown in equation (1).

$$\frac{E-500}{755.6-757.3}=\frac{450-E}{752.1-755.6} \tag{1}$$

Equation (1) gives 483.6 MPa for longitudinal Young’s modulus. For validation, the simulation is implemented with the mentioned properties. The FE analysis presented 755.7 Hz (figure 8) as the system fundamental longitudinal frequency. The error percentage for linear interpolation is negligible and its value is calculated as 0.013%.

$$Err=\frac{755.7-755.6}{755.6}\times 100=0.013\% \tag{2}$$

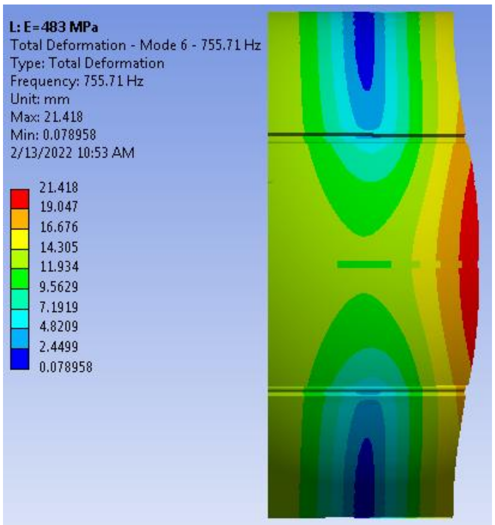


Figure 8. Corresponding mode shape for final investigation

Conclusion

In this paper, the physical and mechanical properties of the stator core stack of a 50 kW PMSM system were extracted. For this investigation, the non-destructive testing method was employed which is a beneficial method with low cost. The results of FE solution are validated with experimental results, and the error percentage is negligible.

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